

Hydrodynamics and Heat Transfer through Corrugated Channels: A Review

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ABSTRACT

The continually rising energy consumption pushes researchers and engineers to create more effective energy systems to better use energy sources. In order to manufacture more compact heat exchangers, which are used in air conditioning systems, chemical reactors, heat power plants and others, it is important to improve the heat transfer rate with an appropriate pressure drop. Currently many engineering strategies are applied to increase energy systems thermal transfer efficiency, such as surface changes, swirl flow creators, flow conditioners, additives etc. Researchers are also involved in applying these methods to further increase the reliability of energy systems, while many experimental and numerical details are available in the existing literature. Since the corrugated channel is a passive technique to maximise heat transfer, researchers have insisted that one or more passive / active methods be used in corrugated channels to allow further changes. The purpose of this paper is to collect accessible research data based on the flow characteristics and the heat transfer rates across corrugated channels in particular. The previously obtained conception conditions, functional limits, and assumptions of energy systems are also discussed.

KEYWORDS: Compact heat exchanger, Heat transfer augmentation, Passive methods, Corrugation, and Pressure drop

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I. INTRODUCTION

In order to increase energy system reliability, the construction of more efficient energy systems is a task for researchers and engineers to minimise energy usage. Improving the rate of heat transfer and thus producing more compact heat exchangers, which are important components for many engineering applications such as space, aeronautics, automobile, ocean thermal energy conversion technology, is a major concern in this regard. Corrugations are used to increase the heat transfer rate and to improve the strength of plates in plate heat exchangers. Complex corrugated channel geometry improves the efficiency of heat transfer, resulting in higher pressure losses, especially in the turbulent flow phase.

Flow control methods include three primary methods: active flow control, passive flow control and compound flow control for heat transfer rate improvements. The **active flow control technology** requires external power input to increase the heat transfer. For e.g., flow oscillation, flow vibration, surface vibration, magnetic field and other related techniques are active flow methods. This example offers better mixing of flow and increased heat transfer. In the **passive flow control method**, no external input is required to enhance the heat transfer; but, due to geometric adjustments, there is a further pressure decrease. The use of inserts, additives, rough surface, swirl flux systems as well as treatment surfaces and extended surface areas as coiled tubes are some examples of passive

flow control approaches. The reduction of the hydraulic diameter of the flow passage increases the transfer rate, as can be seen from examples. In some cases a secondary flow can be achieved using this method, which increases the heat transfer rate through the mixing of fluids between the central flow area and the flow area near the wall surface. The technique of **compound flow control** requires combinations of two or more systems of flow control for heat transfer. An example of the compound flow control technique might be a surface structure with additives or flow vibration with additives.

The corrugated channels are significantly used in industrial heat exchangers as a passive flow control technology to increase the heat transfer rate. This technique is designed to interrupt and reform the flow boundary layer through the channel. The primary objective of this analysis is to review research data covering most forced convection parameters in corrugated channels that increase the rate of heat transfer in a single-phase state. It is also intended to study the technology, relevant design specifications, efficiency, and operating fluid hydrodynamics of corrugated channel heat exchangers in order to provide suitable specifications for engineers and researchers to choose the suitable kind of corrugation, additives or active methods to implement their application under appropriate conditions. In order to enhance heat transfer and hence to identify the flow

feature that promotes heat transfer change across different corrugated channel applications, attention is also given to the implementation of corrugated channels.

II. Important definitions

2.1. Enhancement ratio

In order to demonstrate the effect of the surface modifications on heat transfer, the enhancement ratio E is an important parameter. The ratio of an improved surface (hA) to that of a plain surface $(hA)_p$ [3] is the enhancement ratio, E . Some studies, such as the pulsating flow case, compare the improvement ratio with the steady flow case [4] as;

$$E = \frac{hA}{(hA)_p} = \frac{(Nu)_p}{(Nu)_s}$$

2.2. Thermal performance factor

The thermal performance factor, TPF, is used to measure the performance of energy system modifications, such as channel corrugation or additives. This TPF is defined as the ratio of normalised Nusselt number, Nu / Nu_0 to the normalised friction factor of the, $(f / f_0)^{1/3}$ [5].

$$E = \frac{\frac{Nu}{Nu_0}}{\left(\frac{f}{f_0}\right)^{\frac{1}{3}}}$$

Where, Nu_0 and f_0 represent parallel plate channel Nusselt number, Nu and friction factor, f , respectively. When evaluating TPF, the values of Nu_0 and f_0 are determined for each appropriate situation. For instance, $Nu_0 = 3.77$ is taken for the Nusselt number, Nu of fully developed flow in the parallel plate for laminar flow under the constant wall temperature boundary condition or $f = (0.79 \ln(Re) - 1.64)^{-2}$ is used to calculate the friction factor, f in parallel plates for turbulent flow [6].

2.3. Corrugation pitch (length)

The distance between the neighbouring corrugations is referred to as the pitch of corrugation or length of corrugation, L . It is an important parameter that has remarkable effects on the flow characteristics that contribute to the improvement of heat transfer.

2.4. Corrugation height (amplitude)

This description is used by many researchers as the height, $2a$, of the corrugation beginning from the bottom of the corrugation and to the top of the corrugation. The amplitude, a , is used by another section of the researchers as half of the corrugation that starts from the bottom of the corrugation to the half-height of the corrugation.

2.5. Channel height

The height of the channel, H , which is the area between the walls of the upper and lower channels, is a parameter that must be explored with respect to the thermal efficiency factor, TPF. For any operating parameter, the optimum channel height needs to be calculated.

III. Literature Review

The developments and the enhancements in all the heat transfer equipment's are mainly purposed for energy savings and savings in projects capital investment, through reducing the costs (energy or material). The better heat exchanger is one that transfer's high heat rate

at low pumping power with a minimum cost. The spent of money for the research and development in corrugated plate heat exchangers, in last decades, from some companies, offered different and versatile types and models of that heat exchanger.

3.1. Previous work

Numerous works has been done on Plate Heat Exchangers (PHEs) and their data related to thermal and hydraulic characterization are available in open literature. But there is a widespread discrepancy in these reported correlations and before commencing the present study, it was necessary to analyze the experimental facilities and procedure, data reduction methods, results and conclusions of some of the important past works.

Junqi et al. (2018) has experimentally investigated the thermal hydraulic characteristics for three types of fluids (R245fa, glycol & water) on plate heat exchanger surface. To overall evaluate the enhanced heat transfer, concept of pump power is provided. Using multiple regression method, dimensionless correlation equation of Nusselt number & friction factor are given. It is concluded that the plate chevron angle affect thermal hydraulic performance. Heat transfer increases with increase in chevron angle & vice versa.

Sharif Asal et al. (2018) used Computational Fluid Dynamics approach with the Reynolds stress model to investigate the influence of the apex angle on the thermal and hydraulic features of triangular cross-corrugated heat exchangers. The Reynolds number was varied from 310 to 2064. The numerical results varied by 5% than experimental results. On increasing the apex angle, pressure forces increase which lead to pressure drop along with heat exchanger coefficient. It is concluded that on increasing apex angle from 45° to 150° , vorticity magnitude & pressure forces along the direction of flow increase which lead to higher heat transfer.

Khavin G. (2018) studied about the different height of corrugation for heat exchangers with a circular plate. For designing of such heat exchanger, use of plates with different corrugation heights along hot and cold side can prove to be very helpful. Due to this design, resistance to contamination increases.

Johnson et.al (2017) studied the analytical design of the heat exchanger which has been also numerically analyzed. On the basis of standard $k-\epsilon$ modelling CFD analysis have been done. The solution of the problem yields when the optimum values of flow rate, outer diameter of pipe and inner diameter of pipe to be used at an effective length for a double pipe heat exchanger. When the stream processes for specified flow rates then it was treated for a given inlet to outlet temperature. From the result it has been found that the design and analysis of the double pipe heat exchanger would be a great success.

R K Ajeel et.al (2017) studied CFD study on turbulent forced convection flow of Al_2O_3 -water nanofluid in semi-circular corrugated channel. Computational Fluid Dynamics (CFD) simulations of heat transfer and friction factor analysis in a turbulent flow regime in semi-circle corrugated channels with Al_2O_3 -water nanofluid is

presented. Simulations are carried out at Reynolds number range of 10000-30000, with nanoparticle volume fractions 0-6% and constant heat flux condition. The results for corrugated channels are examined and compared to those for straight channels. Results show that the Nusselt number increased with the increase of nanoparticle volume fraction and Reynolds number. The Nusselt number was found to increase as the nanoparticle diameter decreased. Maximum Nusselt number enhancement ratio 2.07 at Reynolds number 30,000 and volume fraction 6%.

Hasanpour et al. (2016) have experimentally studied a double pipe heat exchanger with inner tube corrugated filled with various categories of twisted tapes from conventional to modified types (perforated, V-cut and U-cut). The twist ratio, the hole diameter, the width and depth ratio of the cuts have been varied and the Reynolds number has been changed from 5000 to 15000. Overall more than 350 experiments were carried out. Nusselt number and friction factor for corrugated tube equipped with modified twist tapes are found out to be higher than typical tapes.

Goodarzi et al. (2015) experimentally investigated the influence of different functional covalent groups on the thermal physical properties of carbon nanotubes – base fluid. Thermal properties such as convection heat transfer coefficient, Nusselt no., friction loss, pressure drop & pumping power were calculated for corrugated plate heat exchanger. Variation in Reynold's no. was done & nano-fluids properties were measured experimentally.

Elmaaty et al. (2015) developed a corrugated plate heat exchanger. The author has presented review related to plate heat exchanger and further on brazed corrugated plate heat exchanger the authors have been worked upon. The author have concluded that additional work & modelling are needed on visualization, calculation & measurements of pressure drop and heat transfer using nano-fluids.

Kabeel A.E et al. (2013) have experimentally tested loop to study the PHE thermal characteristics, heat transfer coefficient, pressure drops etc. at different concentrations of nanofluids. The measured heat transfer coefficient results have been compared with theoretical values. An increase in heat transfer coefficient up to 13%, for a nano-fluid concentration of 4% in laminar flow regime, at constant Re number with 9.8% uncertainty is observed. On using nano fluids, power being transmitted is enhanced. But effectiveness of plate heat exchanger decreases.

Han, Xiao-Hong et al. (2010) have used chevron corrugated plate heat exchanger to obtain three dimensional parameters- temperature, pressure and velocity fields. It was seen that in the first zone, the temperature gradient increases gradually and got the maximum in the central of the flow, the temperature gradient became smaller again. The highest temperature appeared around the upper port, while the lowest temperature appeared in the cold fluid inflow around the lower port. From the flow field, a dead zone where the fluid flow rate is very low departed from corrugated side.

The simulated results have been compared with the experimental values and it was found that results were consistent with those of pressure drop.

Min & et al. (2009) reviewed use of heat exchanger into gas turbines. The authors discussed the work of other researches about the design of a heat exchanger matrix, material selection, manufacturing technology and optimization. A potential heat exchanger designs for an aero gas turbine recuperator, intercooler and cooling air cooler has been suggested based on previous research. It is included that primary surface heat exchanger have relatively larger effectiveness.

Kanaris, Athanasios et al. (2006) used a general purpose CFD code to compute the characteristics of the flow field, and the heat transfer of conduits with corrugated walls. The plates were assumed to be of stainless steel of herringbone design. The code has been validated experimentally for counter current flow of water. It is concluded that CFD is an effective & reliable tool for designing of efficient plate heat exchangers.

Islamoglu Y. & A. Kurt (2004) used artificial neural networks (ANNs) for heat transfer analysis in corrugated channel. Experiments were conducted for processing with the use of neural networks. Back propagation algorithm was used in training and testing the network and an algorithm using C++ has been developed to solve it. The results of ANN approach & experimental varied by about 4%.

J. A. Stasiak (1998) developed liquid crystal technique and applied it to study six element shapes of rotary air heat preheaters. A complete mapping of temperature, heat transfer coefficient and pressure drop has been obtained at every angle and Reynolds number. It is concluded that the presented corrugated-undulated geometry (CU) can be considered as a generalized of the crossed-corrugated geometry.

Vicente & et al. (2004) studied corrugated tubes using experimental techniques to obtain their heat transfer and isothermal friction characteristics. Water and ethylene glycol were used as working fluids. 10 corrugated tube with rib height ranging from 0.02 to 0.06 & spiral pitch from 0.6 to 1.2 were manufactured using cold rolling. It is concluded that heat transfer increases with increase in Prandtl number. Also at low Reynolds number, tubes with height severity index are most advantageous ones.

Chang Y. J. & Wang C. C. (1997) developed a generalized heat transfer correlation for louver fin geometry 91 samples louvered fin heat exchanger with different geometrical parameters, like louver angle, tube width, louver length, louver pitch, fin length and fin pitch. It is concluded that the inclusion of the plate and tube louver fin data in the heat transfer correlation results in a mean deviation of 8.21%

Kondepudi & O'Neal (1991) experimentally investigated fin tube heat exchanger for studying the effects of frost growth on thermal performance of fin tube heat exchangers with wavy and corrugated fins. More frost growth and higher pressure drops were found for higher

air humidity & fin density. It was concluded that frost growth was a function of spacing as well as air humidity. The pressure drop was found to be function of frost growth & heat exchanger geometry. Heat exchangers with smaller fins due to reduction free flow area have higher pressure drop.

Webb R.L. (1981) has extended previous work of Bergles and Webb to establish a broad range of Performance Evaluation Criteria (PEC) applicable to single phase flow in tubes. Detailed procedure have been outlined to calculate the performance improvement and to select the 'optimum' surface geometry. PEC are presented for four design cases: (1) Reduced heat exchanger material; (2) increased heat duty; (3) reduced long mean temperature difference; and (4) reduced pumping power. The cases discussed included fixed flow area and flow area. Appropriate PEC for two phase exchanger's area have been also discussed. It is concluded that modified PEC is applicable to heat exchangers having two-phase flow.

IV. Conclusions

The present work is aimed at collecting usable flow and heat transfer characteristics investigations for all forms of corrugated channels in different applications. The key effects of those studies are stated as follows.

1. Corrugations, when working under acceptable Reynolds numbers, may serve as the heat transfer enhancement method.
2. Corrugations include fluid recirculation and swirl movement at sufficient Reynolds numbers for the channel flows, which are heat transfer amplification mechanisms.
3. Corrugation angles, height, $2a$, volume, height of L and channel, H are major criteria for enhancement of heat transfer and decrease in strain. At an operational range, they should be configured.
4. Other parameters that influence the characteristics of flow and heat transfer are sharp or rounded corrugations. Generally, strongly cornered corrugations have a higher rate of heat transfer and induce a higher drop in pressure. For this cause, sharply cornered corrugations, for example by rounding, should be optimised.
5. If it works under suitable dimensionless numbers such as P , St and Re , pulsating (or oscillating) flows may be used as a heat transfer amplification technique.
6. There is an optimal Strouhal number, St at those Reynolds numbers, and vice versa, to obtain more thermal efficiency when the flow is under pulsation (or oscillating).
7. If it is used with the required volume fraction and the Reynolds number, nanoparticles are another remarkable instrument to provide heat transfer enhancement.

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